

Strategies for reducing the environmental impacts of organic mozzarella cheese production

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ABSTRACT

This study first investigates the environmental performance of 1 kg organic mozzarella cheese production, performing a cradle-to-gate attributional life cycle assessment. The upstream process related to organic milk production contributed the most to the impact category of climate change in the cheese's life cycle. Electricity and water consumption were the main contributors to impacts at the dairy plant level. Then, disregarding the impacts from milk, five scenarios related to technological and management strategies at plant level are proposed, including a new equipment acquisition, changes in the production volume rate, and the use of byproducts to obtain new foods. The use of a cooling tower during milk pasteurization reduced water consumption by 60%. Varying the production volume of the dairy beverage resulted in relevant changes in all impact categories considered. Differences in the volume of mozzarella cheese production did not result in relevant changes in the impact categories. The use of skimmed buffalo milk proved to be a feasible option to produce the Minas frescal light cheese. Also, an inventory of mozzarella cheese certified as organic was obtained. Such results can provide more reliable information to stakeholders regarding product choice and processes with the best environmental performance for the dairy industry.

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1. Introduction

World buffalo milk production is ranked second after that of bovine milk and is also an important source of nutrients, with high contents of fat, lactose, casein, whey proteins, and minerals. It is consumed in liquid form or processed in numerous dairy products like cheese, yogurt, ice cream, butter, and milk powders (Khedkar et al., 2016).

In Brazil, buffalo milk has been used mainly in the production of mozzarella, which is the main product of the dairy industry (Sales et al., 2018). Its production meets the growing trend for healthy and high-nutrient foods (Ahmad, 2013). In addition, mozzarella from buffalo milk has a higher price (70%) than the same cheese made from cow's milk (Brazil, 2016).

The global cheese trade grew by 2.5% in 2017 and is expected to surpass \$100 billion by 2019 (FAO, 2018; TMR, 2014). In view of its

economic benefits, the dairy industry should consider the relationships between its several stages and the related environmental burdens.

According to the Intergovernmental Panel on Climate Change, agriculture and livestock contribute to 25% of greenhouse gas (GHG) emissions (IPCC, 2018). In milk production (at the farm level), the main environmental impacts are from GHG emissions such as nitrous oxide (N₂O) and methane (CH₄) (IDF, 2009). These impacts are due to the use of nitrogen (N) in the form of inorganic fertilizers on pastures, denitrification of N compounds from manure excreted in the grassland, grain production for animal feeding, and by enteric fermentation and management of animal waste, respectively.

Thus, as cited in the literature, the feeding and handling strategies used can influence the impacts of the milk (Soares et al., 2018; Palmieri et al., 2017). In the industrial processing stage (at the dairy plant level), the main environmental burdens on milk processing and dairy production, disregarding the impacts from milk production, are related to the consumptions of electricity, thermal energy, water, and cleaning products (Santos et al., 2017;

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Roy et al., 2009).

Organic food production has emerged as an opportunity to provide healthy products for people. Besides this, in general, is believed that organic food is tastier and more environmentally friendly than conventional products (Dias et al., 2015). Organic production systems follow specific criteria and standards that are audited and certified by a legally constituted body or authority (Orboi, 2013).

Organic production is spread around the world's five continents. Global sales and the market expanded threefold in the past decade. North America and Europe encompass the vast majority of the demand for organic products (96% of global revenues). The Asian market has increasingly prominent retail sales. African organic production is mostly for the export market. While Latin America is a major world producer and exporter of organic products, its internal markets are slowly developing. Brazil has the largest market for organic products in the region, with increasing production and rising consumer awareness (Orboi, 2013).

However, it is evident that organic foods potentially have environmental benefits, mainly due to the non-use of pesticides and the reduction of pollution caused by nutrients. Besides these practices, the loss of biodiversity, soil erosion, runoff leaching, and fossil fuel use are all reduced, contributing to a decrease in the impacts related to global warming in comparison to conventional systems (Dias et al., 2015). In this sense, it is important to use methods that allow us to determine the environmental performance of organic products, identifying the real impacts associated with their production.

Life cycle assessment (LCA) has been widely accepted and used as a method for identifying and evaluating the environmental impacts associated with products' and processes' life cycles (Willers and Rodrigues, 2014). In the past few years, several LCA studies have been performed to identify the environmental impacts and propose improvements to enhance production of bovine milk and dairy products (Carvalho et al., 2018; Seo et al., 2017; Santos et al., 2017).

Studies regarding the environmental impacts of buffalo milk production are recent. Pirlo et al. (2012) performed the first LCA study of buffalo milk on two dairy farms in Southern Italy. Afterward, Pirlo et al. (2014a) used the LCA to assess the environmental impact of buffalo milk production on six farms in Southern Italy. They reported that both, the milk productivity and amount of feed purchased per kilogram of milk are the key points that explain the variability of life cycle assessment results. Other studies related to the main environmental impacts of buffalo milk production were performed in India (Garg et al., 2016), China (Xue et al., 2014), Italy (Pirlo et al., 2014b; Sabia et al., 2018), and Brazil (Soares et al., 2018).

Regarding dairy products, some LCA studies on mozzarella cheese have been performed, such as by Dalla Riva et al. (2017), who assessed the differences between the impacts of Italian mozzarella cheese produced from raw milk and mozzarella produced from curd. Palmieri et al. (2017) assessed the environmental impact of mozzarella cheese made with milk produced from different feeding strategies at the farm level including whey usage or non-usage. Kim et al. (2013) studied the impacts of American mozzarella cheese and found that cattle feed production and farm milk production were the major contributors to most of the impact categories.

Despite the most and main relevant impacts in dairy products derive from the raw milk production stage, previous studies show that the processes at the dairy plant are responsible for a significant share of the impacts in the life cycle of dairy products, and need to be managed and mitigated (Santos et al., 2017; Djekic et al., 2014). Thus contributions to the improvement of the industrial processes should be continuously investigated.

This work proposes to study the environmental performance of organic mozzarella cheese made from buffalo milk, as well as to propose strategies to use byproducts and manage production at the plant level.

2. Materials and methods

The present study performed an attributional life cycle assessment (LCA) of mozzarella cheese certified as organic based on the ISO 14040:2006 (ISO, 2006a) and ISO 14044:2006 (ISO, 2006b) standards.

The product system (baseline scenario) comprises an extensive organic buffalo milk production (dairy farm stage) and a dairy industry (dairy plant stage). The dairy farm stage considered includes the production of mineral salt, homeopathic medicines and buffalo milk (Fig. 1). For milk production, animals are bred in 547.31 ha of non-irrigated organic pasture and are supplemented only with mineral salt. The pasture does not receive chemical pesticides or synthetic fertilizers and is predominantly composed of *Brachiaria decumbens*. Due to the organic certification, homeopathic medicines diluted in sugar and 70% ethyl alcohol are used for sanitary control (UFV, 2009). Its daily consumption is between 3.0 and 5.0 g per animal.

Physical (mass) allocation was used to share the environmental impacts of buffalo milk (73.3%) and meat (26.7%), as recommended by the International Dairy Federation (IDF, 2015). Information on the herd composition and the allocation method are available in supplementary data.

The milking is performed under sanitary conditions, using a mechanical process with a calf at the animal's foot to stimulate milk release. Then, the milk is cooled to $\approx 7^\circ\text{C}$ (45°F) and stored in the tank until delivery to the dairy industrial facility 2 km from the farm. The average daily raw organic milk production is approximately 480 L/day (5.0 kg/animal/day), with 6.75% fat and 3.69% protein content.

Besides animal breeding, the production includes milking and milk cooling activities (Andrighetto, 2011). In addition, not only the organic milk and the animal feed but also the cleaning products (detergents and disinfectants) follow the guidelines for organic production.

Then, the milk is processed in a small dairy plant with average production capacity around 1000 L of milk per day. According to local legislation, this dairy plant has medium polluting potential (Bahia, 2018). The baseline scenario considers that the dairy produces cheeses, butter, and fresh ricotta. The cheeses manufactured are Minas frescal, coalho-type cheese, burrata, and mozzarella, which have similar nutritional compositions and production stages. Since their manufacturing does not result in relevant differences in inputs or emissions, the cheeses were all grouped together and considered as mozzarella cheese. The average solids content of the mozzarella and fresh ricotta was 52.4% and 21%, respectively.

Mozzarella production requires several inputs and resources, such as raw materials, water, and electricity (Djekic et al., 2014). Cheese is also considered the main dairy industry product due to its production volume and highest economic value (Santos et al., 2017).

The byproducts resulting from the cheese production are whey and skimmed milk. Both products were initially considered as having no industrial destination (baseline scenario). The liquid whey and the skimmed milk are sent for animal feed (bovine and swine, for example) and human consumption, respectively.

2.1. LCA objective and scope definition

The goal of the LCA study was to identify the environmental

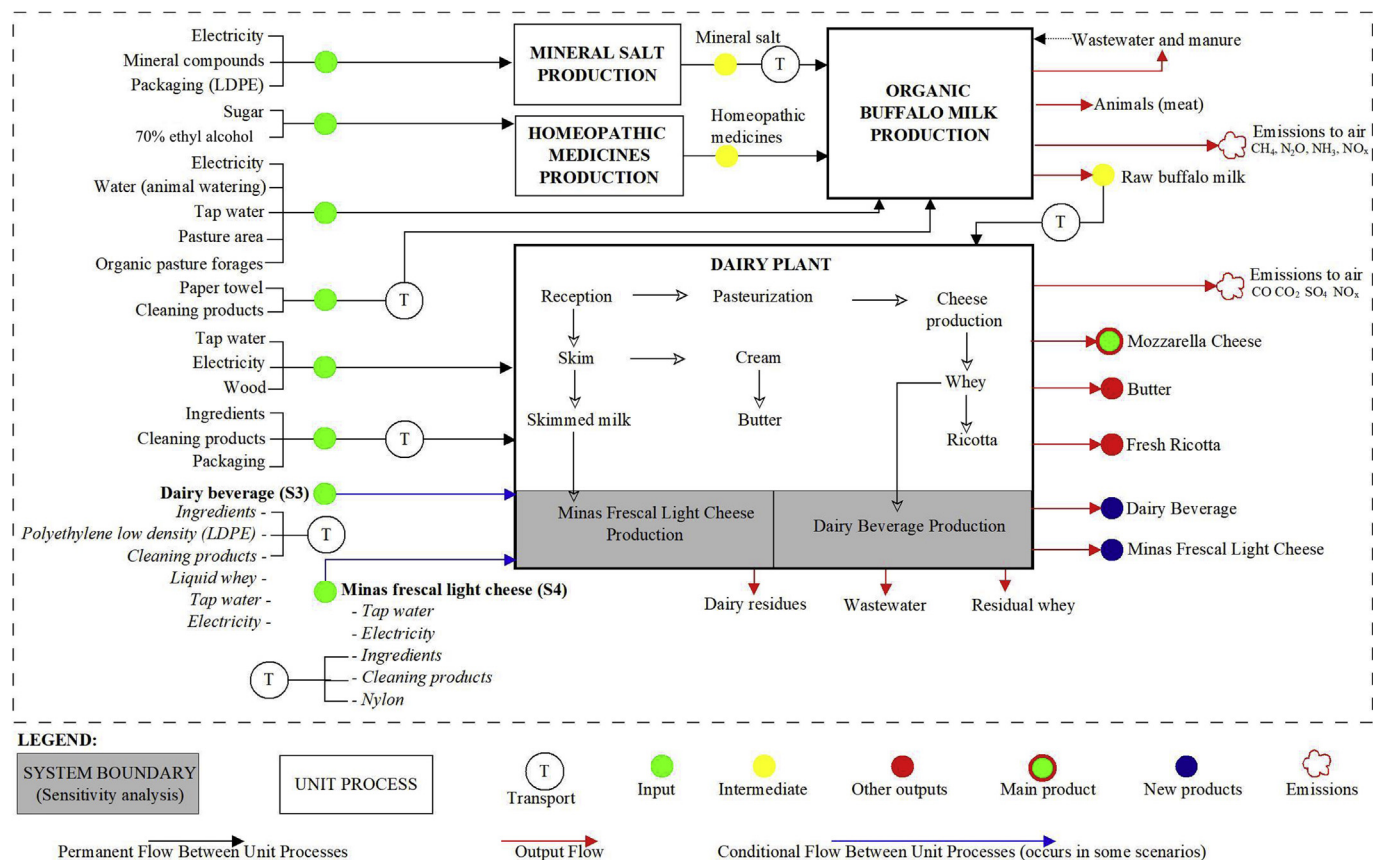


Fig. 1. Product system.

impacts of mozzarella cheese production, certified as organic. Initially, the system boundary included since the organic buffalo milk production to the gate of the dairy plant (cradle-to-gate). Secondly, for modeling the scenarios, the impacts of raw milk production were disregarded, in order to highlight the main elementary flows at the dairy plant level.

According to each scenario proposed, the economic or physicochemical allocations were used for distributing the impacts between mozzarella cheese and other dairy products, according to the International Dairy Federation (IDF, 2015) (supplementary data).

The impact assessment method used was the ReCiPe 2008 (Goedkoop et al., 2009). Baldini et al. (2017) indicated that LCA studies of the milk sector should investigate a wide range of impact categories. Thus, eight midpoint impact categories have been investigated: climate change (CC, kg CO₂eq), ozone layer depletion (OD, kg CFC-11eq), terrestrial acidification (TA, kg SO₂eq), freshwater eutrophication (FE, kg P_{eq}), photochemical oxidant formation (POF, kg NMVOC), particulate matter formation (PMF, kg PM₁₀eq), water depletion (WD, m³), and fossil depletion (FD, kg oil_{eq}). The method and the impact categories were selected according to the objective of the study, based on environmental relevance and on a lesser level of uncertainty associated with the LCA models.

The assumptions of this study were as follows: (i) the environmental impacts resulting from the infrastructure, machines, and equipment of dairy farm and dairy plant stages were not considered; (ii) the impacts of land transformation were disregarded, since milk production has taken place for more than 20 years on this farm; (iii) the use of farm tractors and their consumption of products and lube oils were not considered due to their less frequent use; and (iv) capital goods were disregarded.

The GHG emissions were estimated according to data related to the herd, such as the number and live weight (kg) of animals of each category. The main gases calculated were methane (CH₄) and direct and indirect emissions of nitrous oxide (N₂O), according to the Intergovernmental Panel on Climate Change, Tier 2 and Tier 1 (IPCC, 2006a,b). The daily gross energy required by the animals for maintenance, growth, activity, pregnancy, and work was estimated considering the energy density of the diet (pasture) and the coefficients to each group of animals from the herd (IPCC, 2006a,b).

2.2. Inventory analysis

The data referred to the life cycle inventory (LCI) correspond to the period from January to December 2016 (Table 1). The LCI of mozzarella consists of primary data obtained by in loco verification from a dairy farm and a dairy plant, both in the center-south region of Bahia State, Brazil, whose products are certified as organic. When necessary the inventory considered secondary data according to the most suitable source available.

The geographical region of study is one of the most important areas in the Brazilian northeast for agriculture and livestock because of its excellent soil and climate (Willers et al., 2017). The dairy plant's features are similar to those of 77% of same-sized dairy plants in Bahia State, making it a relevant buffalo milk and dairy producer (Bahia, 2010).

2.3. Impact assessment

SimaPro[®] v.8.5.2.0 software was used to model the product system and calculate the environmental impacts. Initially, the

Table 1

Life Cycle Inventory of 1 kg of mozzarella cheese certified as organic.

	Quantity	Quality ^a	σ^2	Source
INPUTS				
MILK PRODUCTION				
Raw milk	6.838 kg	VD	0.0026	This study
Tap water	3.5 L	ED	0.0429	Willers et al. (2014)
Water (animal watering)	0.016 L	ED	0.0429	Austrália (2003)
Electricity	0.0127 kWh	ED	0.0507	Marques (2000)
Pasture area	1.5E-04 ha	ED	0.0102	(elementary flow)
Organic pasture forages	2.1E-04 kg	VD	0.0102	Agri-footprint ^b
Paper towel	1.6E-03 kg	ED	0.0413	Ecoinvent v.3 ^c
Cleaning products				
Iodine-based sanitizer	2.28E-03 kg	ED	0.1301	Ecoinvent v.3
Peracetic acid	4.92E-04 kg	ED	0.1301	-
Alkaline detergent	2.73E-04 kg	ED	0.1301	Ecoinvent v.3
Nitric acid	1.09E-04 kg	ED	0.1301	-
Sodium hypochlorite	1.03E-03 kg	ED	0.1301	-
MINERAL SALT PRODUCTION				
Mineral compounds				
Sodium chloride	3.84E-03 kg	ED	0.1301	-
Calcium	1.76E-03 kg	ED	0.1301	
Sodium	1.45E-04 kg	ED	0.1301	
Kaolin ore	1.07E-04 kg	ED	0.1301	
Phosphorus	6.59E-03 kg	ED	0.1301	
Sulfur	4.69E-06 kg	ED	0.1301	
Zinc	2.88E-04 kg	ED	0.1301	
Iron	1.54E-05 kg	ED	0.1301	
Copper	1.26E-06 kg	ED	0.1301	
Manganese	1.05E-04 kg	ED	0.1301	
Fluorine	6.50E-04 kg	ED	0.1301	
Iodine	6.08E-05 kg	ED	0.1301	
Cobalt	4.45E-05 kg	ED	0.1301	
Selenium	1.03E-05 kg	ED	0.1301	
Electricity	1.27E-04 kWh	MD	0.0507	USLCI, 2012
Packaging (LDPE)	2.5E-04 kg	MD	0.0507	USLCI, 2012
Transport	2.11E-02 tkm	ED	0.1292	Agri-footprint
HOMEOPATHIC MEDICINES PRODUCTION				
Sugar	0.0198 kg	MD	0.0261	UFV (2009)
70% ethyl alcohol	4.32E-05 kg	MD	0.0261	UFV (2009)
OUTPUTS				
Wastewater	3.5 L	ED	0.0413	Agri-footprint
Paper towel	1.6E-03 kg	ED	0.0413	Ecoinvent v.3
Animals (meat)	1.03 kg	ED	0.0413	(elementary flow)
Emissions to air				
CH ₄ enteric	2.35 kg	ED	0.0120	(elementary flow)
CH ₄ manure	4.4E-02 kg	ED	0.0120	(elementary flow)
N ₂ O (direct)	6.17E-03 kg	ED	0.0120	(elementary flow)
N (leached)	5.48E-02 kg	ED	0.0120	(elementary flow)
N (volatilized)	5.48E-03 kg	ED	0.0120	(elementary flow)
Transport of cleaning products	8.63E-05 tkm	ED	0.1292	Agri-footprint
DAIRY PLANT				
INPUTS				
Tap water	47.0 L	DM	0.0032	Ecoinvent v.3
Electricity	1.61 kWh	MD	0.0032	Ecoinvent v.3
Wood	0.640 kg	ED	0.0507	USLCI
Ingredients				
Sodium chloride	1.3E-03 kg	VD	0.0026	Agri-footprint
Calcium chloride	5.1E-04 kg	VD	0.0026	Ecoinvent v.3
Chymosin enzyme	3.8E-04 kg	VD	0.0026	-
Milk yeast	3.0E-04 kg	VD	0.0026	-
Cleaning products				
Alkaline detergent	6.9E-02 kg	VD	0.0026	Ecoinvent v.3
Peracetic acid	4.55E-04 kg	VD	0.0026	Ecoinvent v.3
Sodium hydroxide	3.19E-03 kg	VD	0.0026	Ecoinvent v.3
Nitric acid	1.12E-03 kg	ED	0.0026	Ecoinvent v.3
Sodium hypochlorite	1.36E-03 kg	VD	0.0026	Ecoinvent v.3
Packaging				
Polyethylene (LDPE)	1.23E-03 kg	MD	0.0092	Ecoinvent v.3
Nylon	1.3E-05 kg	MD	0.0092	Ecoinvent v.3
Corrugated board box	3.05E-03 kg	MD	0.0092	Ecoinvent v.3
OUTPUTS				
Wastewater	47.0 L	ED	0.0413	Agri-footprint

(continued on next page)

Table 1 (continued)

	Quantity	Quality ^a	σ^2	Source
Mozzarella cheese	1.00 kg	VD	-	-
Whey	4.65 kg	ED	0.0120	Ecoinvent v.3
Dairy waste	0.013 kg	VD	0.0026	-
Biochemical oxygen demand	9.82E-04 kg/L	MD	0.0086	LCA Food DK
Chemical oxygen demand	1.54E-03 kg/L	MD	0.0086	LCA Food DK
Plastic waste	0.017 kg	MD	0.0086	-
Ashes	0.0157 kg	MD	0.0086	-
Coal	0.02 kg	MD	0.0086	-
Soot	1.6E-03 kg	MD	0.0086	-
OTHERS				
Transport of milk (from farm to dairy)	9.60E-05 t/km	VD	0.1226	Agri-footprint
Transport of ingredients, packaging and cleaning products	8.40E-06 t/km	VD	0.1306	Agri-footprint

^a **VD** (verified data): data from the production reports in the establishment which were considered for calculations. **MD** (measured data): data and information of high confidence, measured on site during the processing activities. **ED** (estimated data): measures obtained from statements made by professionals and extrapolated in the time scale of one year or, still, from estimated values considering experiences of small-scale measurements carried out on site.

^b <http://www.agri-footprint.com/>

^c <http://www.ecoinvent.org/>

baseline scenario was considered, as previously described, without the use of byproducts and technological improvements.

2.4. Prospective scenarios for improvement of environmental performance at plant level

After the previous impact assessment of the baseline study, some scenarios were proposed in order to improve the critical points identified. Sensitivity analyses were also carried out using the physicochemical and economic allocation methods as well as changes in the production volume of mozzarella cheese.

2.4.1. Change in the allocation method (S1)

As the allocation method can strongly affect results (FAO, 2015), and since there is no consensus on which is the best allocation method for use in multifunctional systems, it is important to know the effects of different methods of allocation on the resulting impacts (Kristensen et al., 2015). Thus, both physicochemical and economic allocation methods were compared.

2.4.2. Using a cooling tower to reduce the water consumption of milk pasteurization (S2)

Water consumption is one of the main critical points in dairy production (Djekic et al., 2014; Santos et al., 2017). A cooling tower is suggested as a technical solution to enhance the milk pasteurization process while reducing water consumption. Besides such benefits, this equipment can contribute to efficiency in the pasteurization process, resulting in better product safety.

This equipment has relatively low acquisition cost (US\$568.27–2654.00), along with easy setup and maintenance. A cooling tower with a capacity of 9000 kcal/h is suggested based on the following parameters obtained from expert consulting: flow, 10–15 m³; initial temperature of raw material, 5–9 °C; final temperature of raw material, 32–34 °C; operating time, 3 h (International refrigeração, 2018).

The results were compared with those obtained for the current system used in the dairy plant, which does not contain such equipment.

2.4.3. Using liquid whey to produce a dairy beverage (S3)

The use of liquid whey for the development of food products has been growing due to their excellent nutritional and functional properties (Jain et al., 2013). Whey can be used for several purposes, especially in the production of dairy beverages once it is a source of proteins and lactose (Prazeres et al., 2014).

The amount of whey produced was estimated based on annual mozzarella cheese production. A mass balance was performed considering the relative density of dairy beverage (approximately 1.028 g/mL 15 °C) and buffalo milk with 5.7% fat and 3.4% protein content.

The dairy beverage production was estimated with the amount of whey used ranging from 10% (6970 kg/year) until the upper limit of 100% (69,700 kg/year), with additional increases of 10%. This last hypothetical scenario considered the maximum installed capacity of the dairy plant. The economic allocation method was used considering the price of US\$1.00/kg for the dairy beverage, according to expert consulting (Scot Consultoria, 2018). The impacts related to equipment acquisition and physical restructuring of the industry were not considered. Information on the inventory of dairy beverage is available in the supplementary data.

2.4.4. Production of minas frescal light cheese (S4)

The choice of healthy foods and the growing cheese consumption around the world, especially in emerging countries, has motivated the dairy industry to develop products for diets with fat restrictions.

Thus, in order to propose a better use for the skimmed buffalo milk resulting from the butter production process, the manufacture of the Minas frescal light cheese was considered. This typical Brazilian fresh cheese is made from cow's milk and is one of the most popular dairy products in the country (Nunes et al., 2016). This product has a relatively low production cost and an easy manufacturing process compared to other fresh cheeses (Dantas et al., 2016).

The consumption of fresh cheeses such as Minas frescal has increased mainly among those with diets with fat reduction or restriction (ABIQ, 2015). The best investment alternatives for the production of Minas frescal in both traditional and light types were studied (Spadoti et al., 2016), though their environmental viability still lacks references.

The production of Minas frescal light cheese with 10 ± 2% and 20 ± 2% fat and protein contents, respectively, was proposed (Laguna, 2018). Based on calculations of the casein balance (6.4 kg skimmed buffalo milk for the production of 1 kg of cheese) and experiments at pilot scale, it was possible to estimate the production volume (1350 kg/year) and the corresponding input flows and resources. The inventory for 1 kg of Minas frescal light cheese is available in the supplementary data.

2.4.5. Changes in the production volume of mozzarella cheese (S5)

Production planning can be considered one of the major

challenges of medium and small dairy plants. Such planning must consider the best possible use of the various distinguishing characteristics of dairy processing (Bilgen and Dogan, 2015). In this study, from the baseline scenario, where the dairy plant processes 480 L/day, a prospective one was modeled increasing the volume of milk in 20% up to near the maximum production capacity of the dairy plant (1000 L/day). The changes in the volume production of mozzarella cheese were modeled considering the same technologies and machinery previously existent.

3. Results and discussion

3.1. Environmental impacts of mozzarella cheese's life cycle

The environmental impacts in 1 kg of mozzarella cheese are presented (Table 2).

As expected, the production of organic buffalo milk was the main contributor to climate change in the life cycle of mozzarella cheese (Fig. 2). The main contributors in this category were the enteric emissions and the emissions from animal waste management system, in this case, manure deposited by grazing animals on fields.

The raw milk had relevant contributions in three impact categories, with 92.3% in CC, 43.2% in TA, and 65.9% in POF. In raw milk production, the direct emissions from the animals, of which 92.1% were associated with enteric methane gas emissions, CH₄, and nitrous oxide, N₂O, from manure deposited by animals on pasture, were the most relevant contributions to the CC category. In TA, the emissions contributed with 41.7% and 23% to PMF.

NMVOG (non-methane volatile organic compound) emissions contributed 99.6% in the POF category. The contributions were 20.9% related to the formation of secondary pollutants of reactions of nitrogen oxide and 78.7% of methane biogenic.

In OD, TA, FE, PMF, FD the flows of electricity and cleaning products were relevant. The Alkylbenzene sulfonate, was the main contributor to cleaning products, ranging from 16.6% to 52.2%. Tap water contributed to 42.2% in WD and less than 5% in the other categories. The electricity used in the milking process and milk storage were not relevant in all the impact categories considered.

In the present study, the GHG emissions for the production of 1 kg FPCM buffalo milk were: 0.34 kg CH₄, 9.02E-04 kg N₂O, 8.01E-03 kg N leached and 8.01E-04 kg N volatilized.

The main environmental impacts driver was the raw buffalo milk, as reported by other studies. Pirlo et al. (2014a) registered average contributions less than 45% in climate change, abiotic depletion (42%), photochemical oxidants formation (80%), and acidification and eutrophication (60%) due to the amount of feed (i.e., maize silage, soybean meal) purchased off-farm and to synthetic fertilizers. Garg et al. (2016) found that buffalo and bovine milk production respectively contributed 22% and 65% of the GHG emissions of mozzarella cheese. Emissions of CH₄, CO₂, and N₂O from cattle contributed 75.4%, 11.0%, and 13.6%, respectively, to the

total emissions of GHG. The contributions of CH₄, CO₂, and N₂O from buffaloes were 80.5%, 8.2%, and 11.3%, respectively, to the total GHG emissions (Garg et al., 2016). Palmieri et al. (2017) performed an LCA in cheese production and reported that the production of raw milk had high contributions (above 90%) in the categories of acidification, eutrophication, photochemical oxidant formation, terrestrial ecotoxicity, land and climate change (78%), abiotic depletion (72%), and ozone layer depletion (73%). The allocation method based on cereal unit (CU) and the low number of lactating animals (<20) can explain the difference in the values for climate change found in this study. Also, the different feeding strategies (with/without silage, with/without liquid whey) corresponded (positively and negatively) to the categories acidification and eutrophication (Palmieri et al., 2017).

Since this work and the literature indicate that the main contributions to the cheese impacts came from raw buffalo milk production and this study focused in the manufacturing processes, the following analysis disregard the milk impact, in order to best identify the hotspots at the dairy plant stage (Santos et al., 2017; Djekic et al., 2014).

3.2. Environmental impacts of mozzarella cheese disregarding the milk as input

Electricity and water consumption were the main contributors to the impacts of the dairy plant. Electricity consumption contributed above 80% in six of the eight categories studied, mainly due to cheese refrigeration: CC (89.9%), OD (76.4%), TA (82.9%), FE (88.7%), POF (84.8%), PMF (85.6%), WD (48.8%), and FD (80.8%) (Fig. 3). The electric motors used for cooling milk products accounted for 96.2% (1.55 kWh) of total electricity consumption.

The main contributor to water depletion was the water required for the pasteurization of dairy products and cleaning of the dairy plant (50.6%).

Djekic et al. (2014) performed an LCA in Serbia of several dairy products and found that electricity flow was the main contributor in five of the seven dairy factories. Among the six dairy products, cheese required the third-most electricity, behind only yogurt and pasteurized milk. Cheese production contributed to climate change (29.1%), acidification (6.5%), and eutrophication (40.3%). Palmieri et al. (2017) reported that cheese production required the greatest amount of energy resources (electric and thermal), so it was considered the main critical point at the factory level where improvements of the environmental profile should be focused. Dairy factories require the use of electricity in engines and refrigeration equipment.

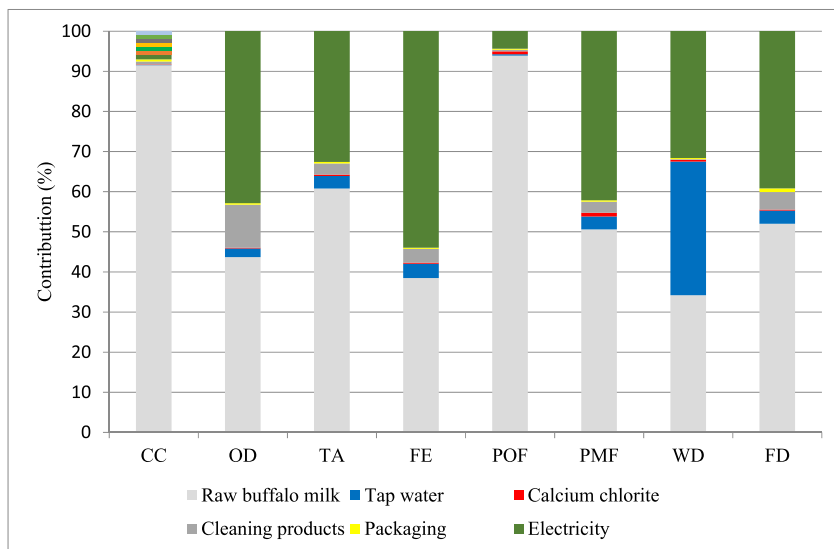
Cleaning products contributed from 5.4% to 18.9% in all categories, acid cleaning with sodium hydroxide being the main contributor in the categories used. Gonzalez-Garcia et al. (2013) also reported that cleaning products contribute to climate change (15%) and eutrophication (4%). Santos et al. (2017) studied changes in the detergents used and obtained differences of less than 2% in the eight impact categories. A pilot-scale study proposed the use of enzymes (proteases and lipases) to remove typical fouling in dairy products, with possibilities to reduce the consumption of energy, water, cleaning products and, thus, the corresponding environmental impacts (Boyce et al., 2015).

The flows of packages, calcium chloride, thermal energy, and wastewater had contributions of less than 2%. The relatively high electrical energy contributions overlapped the share of other input flows in many impact categories.

Santos et al. (2017) assessed the environmental impacts of mozzarella cheese and reported the contributions of electricity as 31.1% for WD and 11.0% for FD. The production of thermal energy contributed 83.3% in OD, due to the emission of carbon

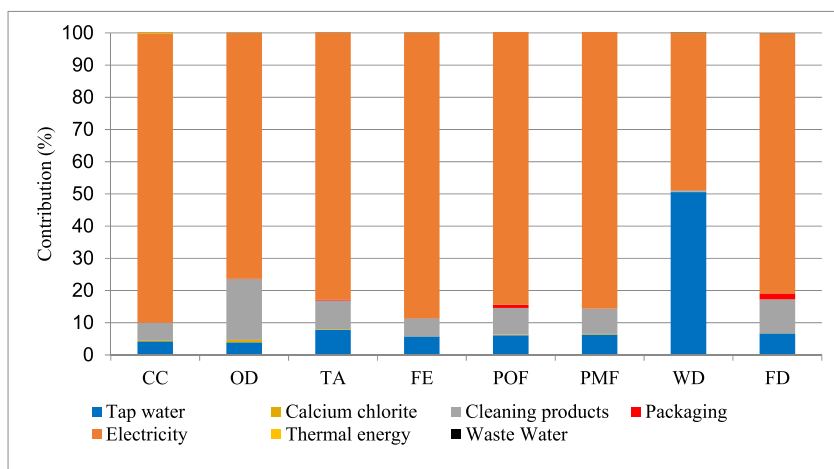
Table 2
Environmental impacts in 1 kg of mozzarella cheese.

Impact categories	Unit	Total
Climate change - CC	kg CO ₂ eq	8.17
Ozone depletion - OD	kg CFC- 11 _{eq}	5.44E-08
Terrestrial acidification - TA	kg SO ₂ eq	4.34E-03
Freshwater eutrophication - FE	kg P _{eq}	1.72E-04
Photochemical oxidants formation - POF	kg NMVOC	5.0E-03
Particulate matter formation - PMF	kg PM10 _{eq}	1.45E-03
Water depletion - WD	m ³	0.113
Fossil depletion - FD	kg oil eq	0.177



CC - climate change, OD - ozone depletion, TA - terrestrial acidification, FE - freshwater eutrophication, POF - photochemical oxidant formation, PMF - particulate matter formation, WD - water depletion, FD - fossil depletion.

Fig. 2. Contribution analysis of the life cycle impact of mozzarella cheese with physicochemical allocation.



CC - climate change, OD - ozone depletion, TA - terrestrial acidification, FE - freshwater eutrophication, POF - photochemical oxidant formation, PMF - particulate matter formation, WD - water depletion, FD - fossil depletion.

Fig. 3. Environmental impacts of mozzarella cheese, disregarding milk's contribution, with physicochemical allocation.

tetrachloride (CFC), and 23.2% in POF and 15% in PMF due to NO_x (86.6%) and particulate emissions of 2.5 μm (PM_{2.5}) up to 10 μm (PM₁₀) in diameter (89.9%). The production of skimmed buffalo milk had relevant contributions to CC (92.7%), TA (98.2%), FE (91.1%), POF (63.5%), PMF (81.4%), and FD (75.2%). The skimmed buffalo milk mentioned in this study has at most 2% fat content and is used exclusively for industrial purposes.

Kim et al. (2013) performed a cradle-to-gate LCA of cheese processing in the United States and found the consumption of electricity, natural gas, and cleaning products to be the main critical points at the dairy plant level.

3.3. Scenario analyses

Five scenario analyses (allocation methods, water management

strategy, valorization of byproducts, the manufacture of a new product and change in the production capacity) were performed in order to test the robustness of the results and management strategies. The first analysis evaluated how an allocation strategy can influence the environmental impacts per kg of cheese, the second assessed the trade-off of an alternative strategy to reduce the water consumption. The third, fourth and fifth scenarios assessed the effect of using a byproduct, the production of a new product and of increasing production capacity.

3.3.1. Changes in the allocation method (S1)

Baldini et al. (2017) reviewed 44 studies of LCA related to the production and processing of milk and dairy coproducts and suggested the use of more than one functional unit, aiming to provide a possible harmonization between the LCA studies. Feitz et al. (2007)

performed four allocation procedures for several dairy products in 17 dairy plants in Australia and showed differences of around 20% between the economic and physicochemical allocation methods for the electricity used in cheese production.

Considering the results obtained, there was an increase in the contribution of mozzarella cheese production in all impact categories when physicochemical allocation was replaced by economic allocation (Fig. 4). Differences in the two allocation methods were higher: 31.8% (CC), 40.5% (OD), 43.6% (AT), 33.9% (FE), 48.4% (POF), 61.1% (PMF), 18.1% (WD), and 67.7% (DF). Electricity, alkaline detergent, and water were the main contributing flows, in that order.

CO₂ emissions were approximately twice as big with the economic allocation than with the physicochemical allocation. Such emissions originate from the burning of fossil fuels (natural gas, fuel oil, and coal). Alkaline detergent, composed mainly of alkylbenzene, was the second flow that resulted in major contributions in the categories used. This was not previously detected when the physicochemical allocation was used.

The result of contributions should be carefully considered due to the lack of an official, standardized allocation method for dairy products. Information on the environmental impacts of the production and processing of organic buffalo milk is very scarce, suggesting that further studies could be conducted using more impact categories and other functional units to support decision-making.

3.3.2. Use of water cooling tower in the pasteurization process (S2)

The use of a water cooling tower influenced all impact categories (Fig. 5). This was expected since this equipment has a higher electricity requirement.

The proposed cooling tower provided an interesting option to reduce water consumption (by up to 90%) and, consequently, the volume of wastewater, with a potential short-term financial return on investment. On the other hand, it resulted in an increase in the other impact categories, indicating the need to consider priorities and trade-offs in decision-making.

3.3.3. Use of liquid whey for production of dairy beverage (S3)

Dairy beverages, marketed worldwide, are one of the most traditional sources of probiotic bacteria, which have health benefits (Tamang et al., 2016).

The amount of whey for the production of dairy beverage was estimated based on technical information and mass balance calculation. Varying the production volume of the dairy beverage resulted in relevant changes in all impact categories considered (Fig. 6).

Increasing production of dairy beverage from 10% to 40% of capacity resulted in increases of above 36% in the categories CC (49.6%), OD (41.6%), TA (43.9%), FE (48%), POF (36.3%), PMF (36.3%), and WD (53%). The impacts had a higher increase in the range of 30–40% in most of the categories considered. Going from 40% to 100% resulted in increases of less than 10% in CC, OD, FE, and FD and around 15% in TA and WD.

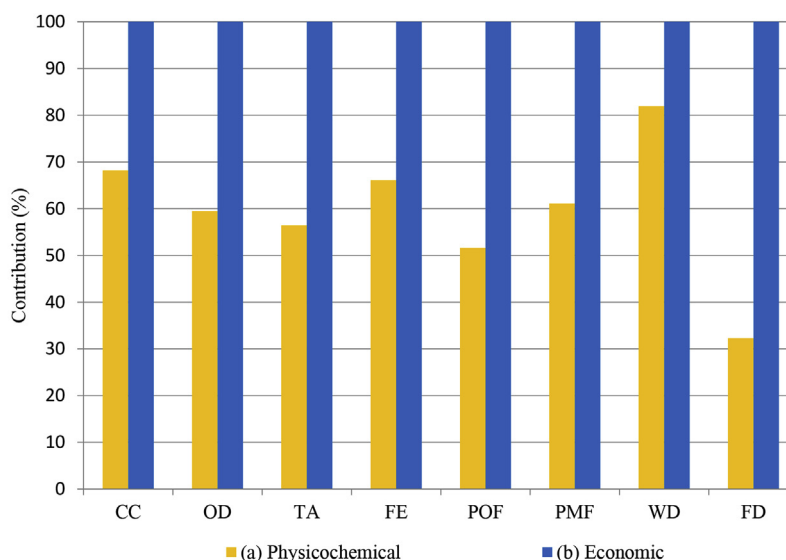
Thus, the strategy of using whey to produce a dairy beverage needs to consider that from 40% of production volume, the contributions to the impacts are not as relevant as in the volume ranges of 10%–40%. This can contribute to deciding the best way to reuse this byproduct.

The neutral detergent, sugar, packaging, and electricity were the main contributors to the impact categories considered. Water, potassium sorbate, nitric acid, sodium hypochlorite, and thermal energy contributed to less than 5% of impacts.

Some studies have considered the use of whey in feeding animals such as swine (Grinstead et al., 2000) and dairy cattle (Palmieri et al., 2017). However, this option precludes the possibility of using whey to manufacture other food products for human consumption (Prazeres et al., 2014).

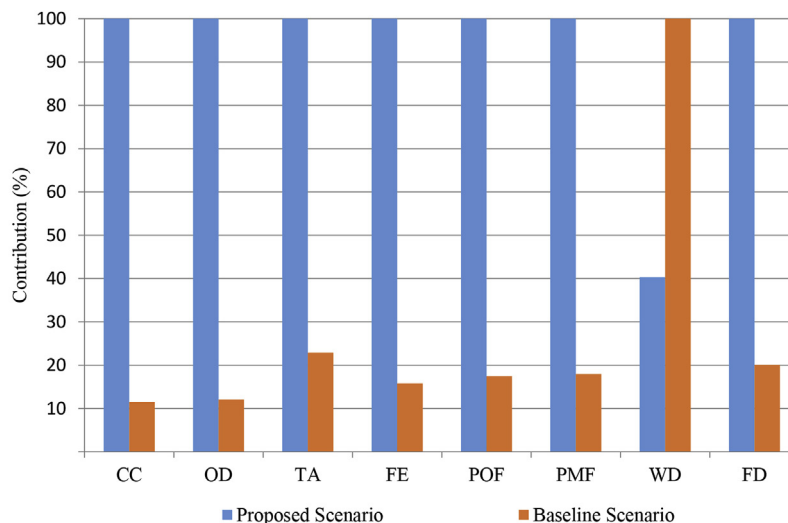
3.3.4. Use of skimmed buffalo milk to produce minas frescal light cheese (S4)

The production of this dairy product influenced all impact categories, highlighting the flows of electricity, nylon packaging, and alkaline detergent (Fig. 7). Electricity was the main contributor flow in most categories: CC (64.1%), TA (45.9%), FE (69.3%), POF (47.9%), and PMF (55.6%).



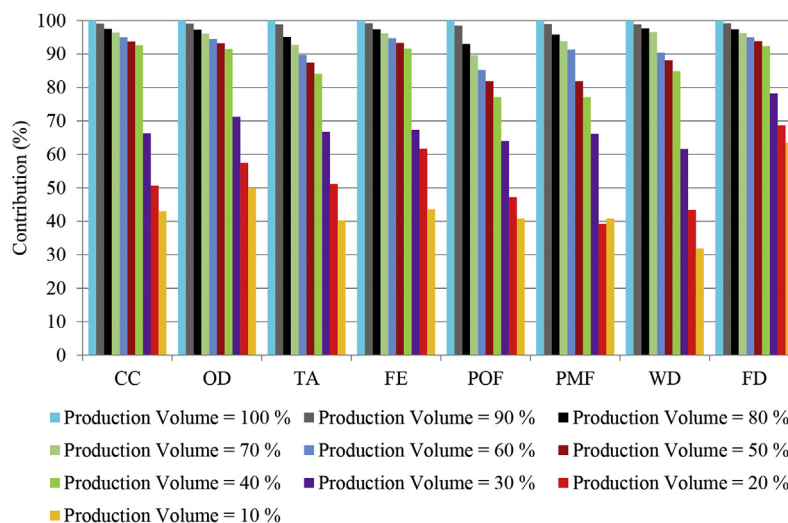
CC - climate change, OD - ozone depletion, TA - terrestrial acidification, FE - freshwater eutrophication, POF - photochemical oxidant formation, PMF - particulate matter formation, WD - water depletion, FD - fossil depletion.

Fig. 4. Environmental impacts of mozzarella cheese using the physicochemical and economic allocation methods.



CC - climate change, OD - ozone depletion, TA - terrestrial acidification, FE - freshwater eutrophication, POF - photochemical oxidant formation, PMF - particulate matter formation, WD - water depletion, FD - fossil depletion.

Fig. 5. Impacts due to the water cooling tower, with economic allocation.



CC - climate change, OD - ozone depletion, TA - terrestrial acidification, FE - freshwater eutrophication, POF - photochemical oxidant formation, PMF - particulate matter formation, WD - water depletion, FD - fossil depletion.

Fig. 6. Potential impacts of varying the amount of dairy beverage production, using the economic allocation.

In the OD category (68.8%), the main contributions were from adipic acid ($C_6H_{10}O_4$), a source of nitrous gas (N_2O). In the WD category (48.6%), emissions of methane (CH_4) arising from the inputs of water treatment were the main contributors. In FD (40.6%), gas emissions and residues arising from the production of alkaline detergent were predominant.

3.3.5. Increasing the production of mozzarella cheese (S5)

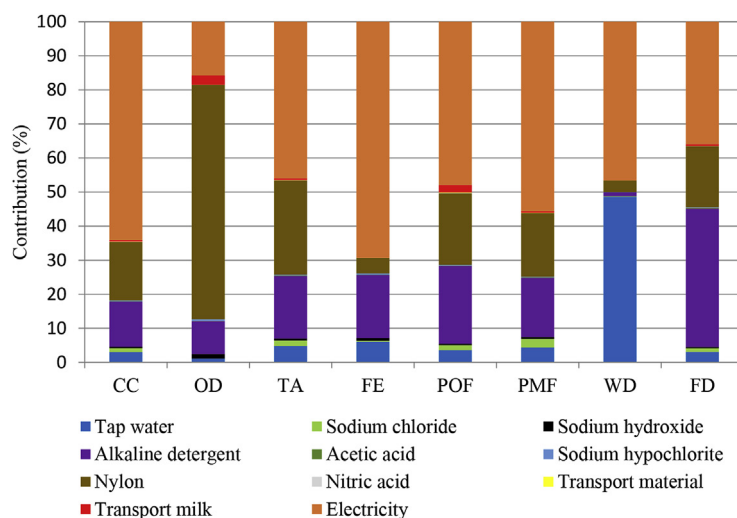
Changes of 20%–100% in the production volume of cheese resulted in not relevant increases (less than 7.5%) in most of the impact categories considered, except for WD (13.2%), (Fig. 8).

Brazilian legislation allows fresh raw milk to remain for 48 h under cooling before it is industrially processed (Brazil, 2011). Thus,

considering that the dairy plant is operating below its maximum capacity and that the buffalo milk production would not increase, it is suggested that the milk production could be stored according to legislation. This would accumulate a volume near to the maximum capacity of the dairy plant, which would operate every two days reducing the consumption of water by around 38% (in the milk reception and pasteurization stages) and cleaning products (nitric acid, 50%, and alkaline detergent, 14%, in the pasteurization stage).

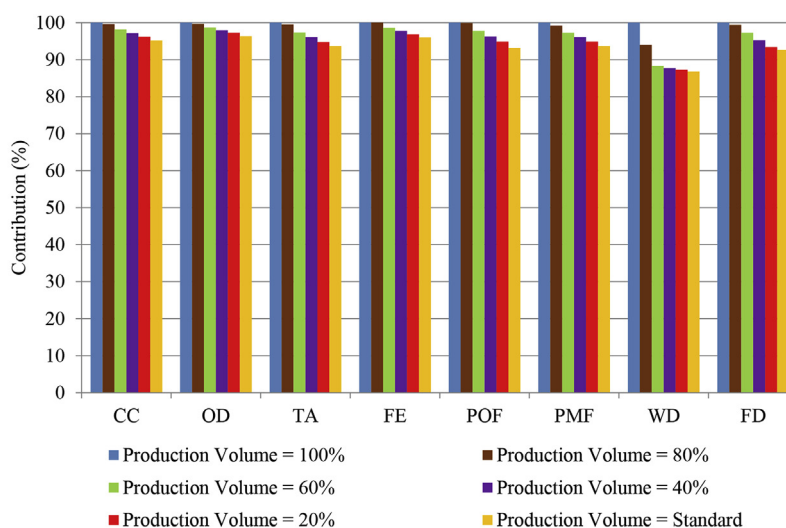
4. Conclusions

This work assessed the environmental impacts of the organic mozzarella cheese made from buffalo milk in Brazil and presented



CC - climate change, OD - ozone depletion, TA - terrestrial acidification, FE - freshwater eutrophication, POF - photochemical oxidant formation, PMF - particulate matter formation, WD - water depletion, FD - fossil depletion.

Fig. 7. Impacts of the production of Minas frescal light cheese, with economic allocation.



CC - climate change, OD - ozone depletion, TA - terrestrial acidification, FE - freshwater eutrophication, POF - photochemical oxidant formation, PMF - particulate matter formation, WD - water depletion, FD - fossil depletion.

Fig. 8. Results for different volumes of cheese production, using the physicochemical allocation.

strategies to management at the plant level. Although milk production at farm was the main contributor in some impact categories, this work also performed a gate-to-gate approach, which allowed to identify the main contributors at the plant level.

Electricity and water consumption required for cheese refrigeration and the pasteurization and cleaning processes, were the main contributors at this perspective. The impacts from electricity were relevant in the categories ozone layer depletion, terrestrial acidification, freshwater eutrophication, particulate matter formation and fossil depletion, while the water consumption was relevant in the category water depletion.

Differences between the emissions per kg of organic mozzarella cheese from the two allocation methods suggest that further

studies need to be performed to support the best decision-making.

The suggestion to use a water cooling tower proved to be an interesting trade-off. The decision for its use cannot consider only the benefit related to the reduction of water consumption since the increases in the other impact categories were relevant.

The option to manufacture new products using byproducts proved to be an option to improve the dairy plant's product portfolio. This could be an opportunity to increase its number of clients and their market share.

The use of the whole installed capacity for cheese production is an attractive proposition that usually does not require changes in factories' physical structures. Most of the improvements are obtained using simple technologies or management strategies.

It is expected that the results of this study will help producers, researchers, and governments make better decisions about strategies related to the use of byproducts, management and technological improvements in small and medium-sized factories.

Furthermore, the results can serve as a basis to assess the environmental potential of organic buffalo dairy products, offering more reliable information for the development of more sustainable products, byproducts, and processes.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2019.03.006>.

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